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EDITORIAL

Atomic Layer Deposition for Energy and Environmental Applications

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There is a critical need for technological innovation to address the increasingly daunting environmental and energy challenges facing humanity in the 21st century. In particular, clean and sustainable energy conversion and storage solutions require advanced materials capable of improving efficiency and reducing costs. Material surfaces and interfaces play a critical role in energy and environmental applications, including solar cells, batteries, fuel cells, supercapacitors, catalysts, sensors, and many other devices. In fact, the bottleneck to performance and efficiency is often directly related to interfacial composition and structure, which requires new strategies to precisely tune interfacial properties. For example, interfacial composition and structure dictate the kinetics of charge and ion transfer in electrochemical devices, built-in electric fields in space charge regions, recombination kinetics in semiconductors, and reaction kinetics on catalyst surfaces.

Engineering of advanced material interfaces requires advanced surface and interfacial modification techniques, which are capable of rational design and tunable synthesis, rather than relying on poorly controlled formation of interfaces and interphases. This is particularly critical for nanostructured materials, as the surface-to-volume ratio increases as feature sizes decrease, resulting in an increasing role of surface and interfacial chemistry on system performance. Often, the synthesis of a desired material or structure results in compositional and structural variations at surfaces and interfaces that are an inevitable consequence of processing and manufacturing. For example, the formation of solid electrolyte interphase (SEI)

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layers in batteries occurs as soon as a solid electrode/liquid electrolyte interface is formed, which affects battery performance throughout its lifetime. Interfacial defects at p-n junctions in photovoltaics directly impact both carrier recombination and charge transport kinetics. This also occurs in photoelectrochemical cells, which further suffer from photocorrosion in the presence of aqueous electrolytes.

To address theses challenges, Atomic Layer Deposition (ALD), and its organic analog Molecular Layer Deposition (MLD) have emerged as powerful techniques for the rational design and synthesis of materials interfaces. ALD and MLD are based on sequential exposure of a substrate surface to precursor vapors, which exhibit self-limiting reactions with surface functional groups. This allows for sub-nanometer precision in film thickness, as well as tunable composition by sequential incorporation of elements in a programmable manner. As a result of the self-limiting nature of the surface reactions, ultra-high aspect ratio structures can be conformally coated without gradients in thickness or composition. Additionally, the deposited material phase, microstructure and morphology can often be adjusted by control of process parameters, providing additional parameters that can be tuned for rational control of interfacial performance.

In this Special Issue, an invited collection of 11 original research articles and 5 review articles are presented from experts in the ALD community, with a focus on energy and environmental applications. The applications covered span photovoltaics, batteries, supercapacitors, photoelectrochemical cells, transparent electrodes, sensors, and environmental barrier layers. The articles reflect the breadth of the ALD and MLD techniques for surface and interfacial modification, and demonstrate the precise control of composition and structure at the nanoscale afforded by their self-limiting chemistry.

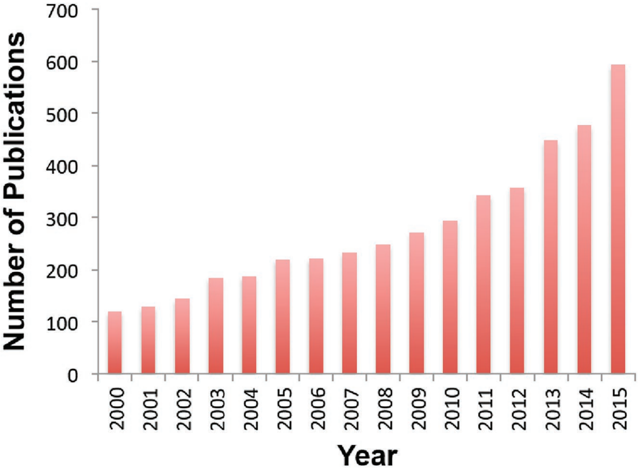

Figure 1. Number of publications with topics containing “Atomic Layer Deposition” and “energy”.[1]

The explosion of ALD research over the past two decades has been heavily influenced by the needs of the semiconductor industry. As the dimensions of devices has continued to shrink and geometric complexity has increased, the ability of ALD to deposit conformal, pinhole-free films with sub-nanometer precision has enabled us to continue on our path along Moore’s law. However, while much attention has been paid to ALD for semiconductor applications, there has been a dramatic increase in the number of publications on “emerging areas”, with energy applications being one of the largest growing sectors. A search with the topic keywords “Atomic Layer Deposition” and “energy” in the Web of Science database from Thompson Reuters[1] demonstrates this continually increasing trend (**Figure 1**). This increase in research activity is also reflected by the growing number of symposia dedicated to ALD for energy and environmental applications. In the future, it is expected that continued advances in the application of ALD and MLD for energy and environmental applications will be driven by the continually increasing knowledge base on materials interfaces in devices, which will lead to commercialization of these fundamental scientific advances. This will require additional research on scalable ALD and MLD manufacturing platforms capable of high throughput, low-cost, and high precision deposition on a wide range of substrate sizes and geometries. While the challenges for scale-up remain significant to meet the economic barriers facing entry into the energy sector, the unparalleled resolution afforded by ALD and MLD chemistry indicate that the future is bright for transformative technologies that can make a significant impact on the energy and environmental challenges facing humanity.

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[1] September **2016**, http://ipscience.thomsonreuters.com/product/web-of-science/